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Transitioning towards negative CO_2 emissions

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ABSTRACT

In this policy perspective we argue that mankind likely needs to achieve negative CO_2 emissions before 2050, describe the transition to CO_2-neutrality and CO_2-negativity, and illustrate the possibly critical role played herein by CO_2 use.

1. Introduction

In order to reach the 1.5 °C maximum temperature increase target of the Paris Agreement, either or not with a temporary overshoot of 2 °C during the 21[st] century, mankind has to achieve net zero CO_2 emissions in 2050 (IPCC, 2018). This conclusion by the IPCC Special Report on "Global Warming of 1.5 °C", published in October 2018, has received ample attention in policy making circles and the media. Much less public consideration has been given to the fact that after 2050 substantial net negative CO_2 emissions need to be realized in order to comply with the ambition of not letting the average atmospheric temperature increase exceed 1.5 °C. A net negative balance of CO_2 emissions implies that more CO_2 has to be taken out of the atmosphere than human activities emit into it. We can think of at least six reasons why negative CO_2 emissions should perhaps already materialize before 2050.

First, least developed countries may not be able to achieve a net zero CO_2 economy by 2050, since the availability of cheap fossil fuels is today often still the fastest way to fulfill aspirations of stimulating growth and eradicating poverty. The possibly positive CO_2 emissions in 2050 of some developing countries need to be compensated by negative CO_2 emissions in developed countries, as industrialized nations are responsible for the lion's share of cumulative CO_2 emissions. Second, certain developed countries may fail to reach their net zero CO_2 emission reduction targets, e.g. as a result of a lack of internal political will to transform their economies away from fossil fuels, or because the inertia of the carbon lock-in proves too strong. Their net CO_2 emissions in 2050 must be counterbalanced by negative emissions from other developed countries. Third, in agriculture, forestry and land use (AFOLU) it may be more difficult to reduce CO_2 emissions than in the use of fossil fuels and industry (FF&I). Net positive CO_2 emissions in 2050 in AFOLU need to be compensated by negative emissions in FF&I. Fourth, within FF&I, for some sectors like aviation and shipping it may be hard to achieve CO_2-neutrality over the next 30 years. Their possibly remaining emissions by 2050 should be offset by negative CO_2 emissions in, for instance, the electricity sector where the switch to zero-CO_2 options is easier and less costly. Fifth, the assumption of net-zero CO_2 emissions strongly depends on substantial emission reductions for two other important greenhouse gases, CH_4 and N_2O (IPCC, 2018), which are usually harder to control and more expensive to mitigate. A potential failure to achieve significant CH_4 and N_2O emission reductions over the next few decades must be counterweighed by negative CO_2 emissions before 2050. Sixth, net CO_2-neutrality in 2050 yields an approximately 70% probability of reaching the 1.5 °C goal of the Paris Agreement. If one wants to raise this probability to e.g. 90%, net CO_2 emissions need to be negative in less than 30 years.

The work by the IPCC heavily hinges on scenarios developed by integrated assessment models (IAMs; IPCC, 2018). The two main options available in most IAMs for implementing net zero or negative CO_2 emissions are (1) AFOLU, and (2) BECCS (biomass energy in combination with CO_2 capture and storage, or CCS). Thus far, IAMs have rarely accurately simulated a third category of methods for realizing net zero or negative CO_2 emissions, that is, processes that use CO_2 as main building block for the production of chemicals, hydrocarbons, materials, and plastics (often referred to as CO_2 capture and usage, or CCU). These alternatives can deliver a "circular carbon economy" (see, for instance, Stahel, 2016). In such an economy all carbon-based products are manufactured from renewable carbon feedstock, either via direct

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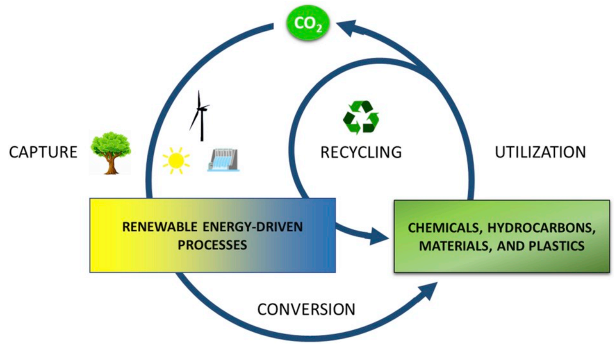

Fig. 1. An idealized circular carbon economy.

atmospheric CO_2 capture (also called direct air capture, or DAC; see Keith, 2009; Lackner et al., 2012), or indirectly via the conversion of waste or biomass derived from natural photosynthesis. We assume that the energy required to drive the capture, conversion, utilization, and recycling processes in an idealized circular carbon economy is provided by CO_2-free renewable resources (see Fig. 1).

The use of CO_2 – or more generally the application of carbon circularity – for the production of chemicals, hydrocarbons, materials, and plastics is at present an activity of around 545 $MtCO_2$/yr (mostly for the manufacturing of urea and biofuels, and the recycling of packaging; see Table 1; Aresta et al., 2013; Armstrong and Styring, 2015; Mikkelsen et al., 2010). This amount is negligible in comparison to today's level of around 38 $GtCO_2$/yr anthropogenic CO_2 emissions. Based on potential average growth extrapolations drawn from the literature, we calculate that the level of CO_2 used in a circular carbon economy could become about 14 $GtCO_2$/yr in 2050 (see Table 1, as well as the online appendix, in which we specify in detail all underlying assumptions). We determine this number by estimating the possible future demand of CO_2 for the production, in particular, of: (A) chemicals, such as alcohols (for instance methanol) and fertilizers (notably urea); (B) hydrocarbons like bitumen and tar e.g. for roads (and applications like roofing), but also fuels and lubricants e.g. for transport (such as in trucks, ships, and planes) (C) materials for construction (e.g. $CaCO_3$ and $MgCO_3$ for concrete); and inorganic salts (e.g. Na_2CO_3); and (D) a large variety of plastics and fibers for packaging, textiles, and construction (including e.g. machinery) part of which ends up in landfill. The (short cyclic) fabrication plus use processes behind most carbon-based products listed in Table 1 can lead to net zero CO_2 emissions (here called 'type I'). A share of the utilized CO_2 is stored in products for at least decades – usually centuries or more – and thus offers a potential for (long cyclic) negative CO_2 emissions (called 'type II'). We argue that the numbers listed in Table 1 ought to be accounted for in IAMs if these models are to adequately inform policy makers regarding the feasibility of reaching the Paris Agreement (cf. Gasser et al., 2015; Andersen and Peters, 2016; Kätelhön et al., 2019).

In Fig. 2 we show how the demand for CO_2 in a gradually more circular carbon economy could grow from 545 $MtCO_2$/yr today to 14 $GtCO_2$/yr in 2050 (depicted on the positive y-axis as the sum of our four categories, including both type I and II use). Four main options can supply the CO_2 required to meet this demand (shown on the negative y-axis): biomass, DAC, large CO_2 point sources (fossil fuel based or in industry), and recycling and waste streams (see the online appendix for our underlying assumptions). For each of these alternatives we assume feasible growth rates, such that supply matches demand. The first two options capture CO_2 from the atmosphere and yield net zero or negative CO_2 emissions. The third option adds CO_2 from fossil resources or minerals to the economy and at best involves net zero CO_2 emissions – although attractive for early CO_2 use projects, this route should ultimately be limited to nearly unavoidable emissions (e.g. from cement plants). The fourth option prevents additional release of CO_2 into the atmosphere by reusing, recycling, and reconverting carbon-based products before incineration, and thereby lowers the overall demand for CO_2.

The circular carbon economy that we project for 2050 can yield negative CO_2 emissions, as demonstrated in Fig. 3 illustrating the CO_2 streams captured, converted, and utilized in processes driven by renewable energy. Chemicals, hydrocarbons, materials, and plastics – that can be produced via many kinds of conversion methods (Ampelli et al., 2015; Bazzanella and Ausfelder, 2017; Detz et al., 2018; GCCSI, 2011) – can jointly store CO_2 at a level of about 14 $GtCO_2$/yr, either temporarily or on a longer time scale. Emissions of CO_2 can result from combustion, decomposition, and incineration of these products over starkly diverging timeframes. Some products can be recycled after a relatively short lifetime, while others store CO_2 for centuries or more. If the quantity of CO_2 stored annually in products exceeds the amount of CO_2 produced from remaining fossil fuel usage and industry, the atmospheric CO_2 concentration decreases, in our case by 2 $GtCO_2$/yr. Changes in AFOLU, as well as the realization of BECCS, could further lower the ambient CO_2 concentration.

Different IAMs adopt broadly varying realizations of AFOLU and BECCS to achieve net negative CO_2 emissions, as exemplified by the four pathways (P1 to P4) described in IPCC (2018). In Fig. 4 we show how global net CO_2 emissions could become negative before 2050 if one gradually transitions towards the circular carbon economy described above. We assume that CO_2 emissions from fossil fuels and industry reduce significantly (but not down to zero) thanks to zero-carbon options like renewables and CCS, energy efficiency, and CO_2 use (the latter e.g. via renewable transport fuels; see pathways P2, P3 and P4 in IPCC, 2018). We also assume that as a result of sustainability practices, CO_2 emissions from AFOLU decline to zero by 2050 (see pathway P4 in IPCC, 2018), while BECCS by then yields negative emissions of 2 $GtCO_2$/yr (in line with pathway P2 in IPCC, 2018). We suppose that also CO_2 use delivers a net effect of negative emissions in 2050 at a level of 2 $GtCO_2$/yr, in accordance with Fig. 3. In this overall projection, net negative CO_2 emissions of around 2 $GtCO_2$/yr are reached before 2050. Although the use of CO_2 today is small in comparison to total anthropogenic CO_2 emissions (Abanades et al., 2017; MacDowell et al., 2017), in our scenario a circular carbon economy would make a meaningful contribution to achieving CO_2-neutrality before 2050.

Table 1
Potential for carbon-based products with CO_2 (equivalents) as feedstock.

Main categories	Subcategories	CO_2 demand ($MtCO_2$/yr)			References
		2015	2050 type I	2050 type II	
Chemicals	Alcohols and fertilizers	145	1200		(Alvarado, 2016; IFA, 2017; OCI, 2016)
Hydrocarbons	Bitumen and tar	< 1		1100	NAPA/EAPA (2011)
	Fuels and lubricants	240	6500		(IRENA, 2018; Lindemann, 2018; Shell, 2018)
Materials	Concrete and salts	30		2000	(Sandalow et al., 2017; Scrivener et al., 2016; Zevenhoven et al., 2006)
Plastics	Packaging and textiles	41	1900		Geyer et al. (2017)
	Construction and landfill	89		900	Geyer et al. (2017)
	Total	**545**	**9600**	**4000**	**13600 $MtCO_2$/yr in 2050**

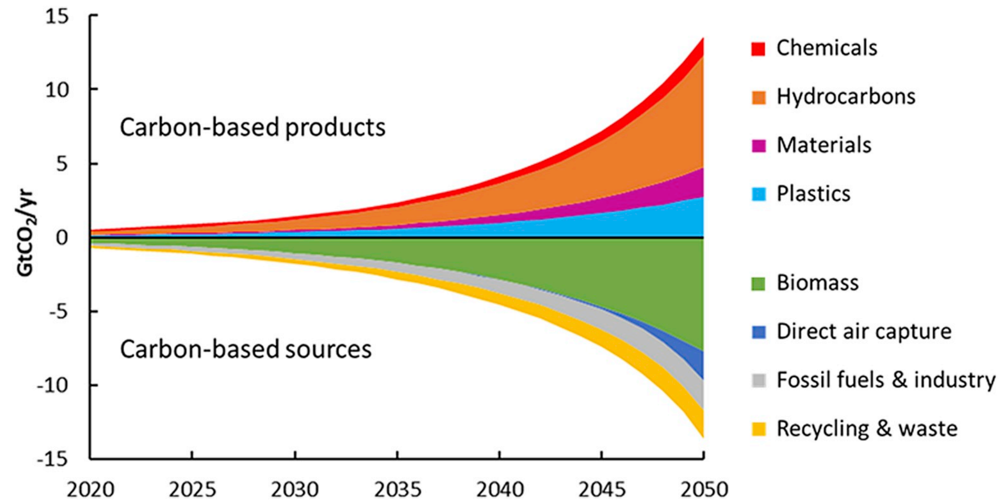

Fig. 2. Projected growth of CO_2 demand and supply.

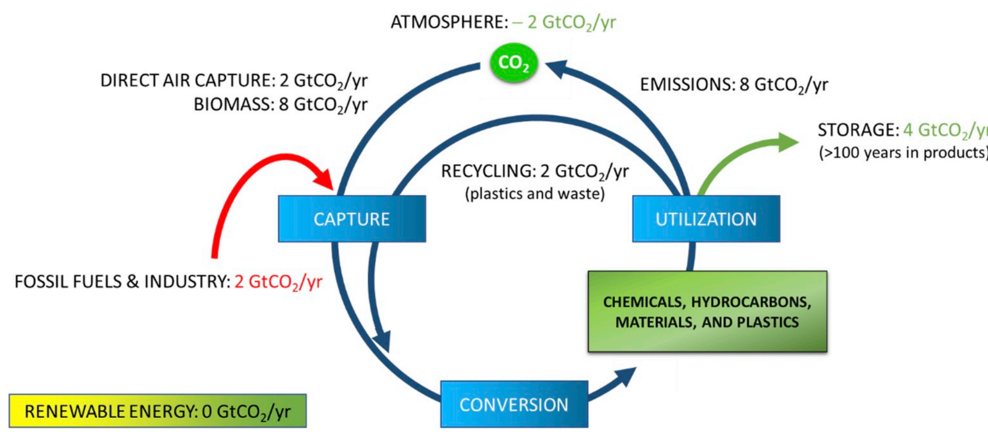

Fig. 3. Main elements of a circular carbon economy in 2050 with net negative CO_2 emissions.

In conclusion, we argue that mankind should prepare for achieving net negative CO_2 emissions before 2050. Observations that during recent years global greenhouse gas emissions have been increasing reinforces this view. We here have shown that CO_2 use can contribute meaningfully to achieving net negative CO_2 emissions before 2050. The technical means to do so, while available on the drawing board and in laboratories, cannot yet readily be scaled up to the required volumes. We therefore recommend to step up RD&D efforts into a broad set of CO_2 use processes, to determine which approaches work best and can operate with the lowest possible cost, energy penalty, and environmental impact (Artz et al., 2018; Detz et al., 2018; van der Giesen and Kramer, 2014). The broader societal requirements and implications of CO_2 use also need be studied in depth and from a multidisciplinary perspective. Such research may confirm that more opportunity for

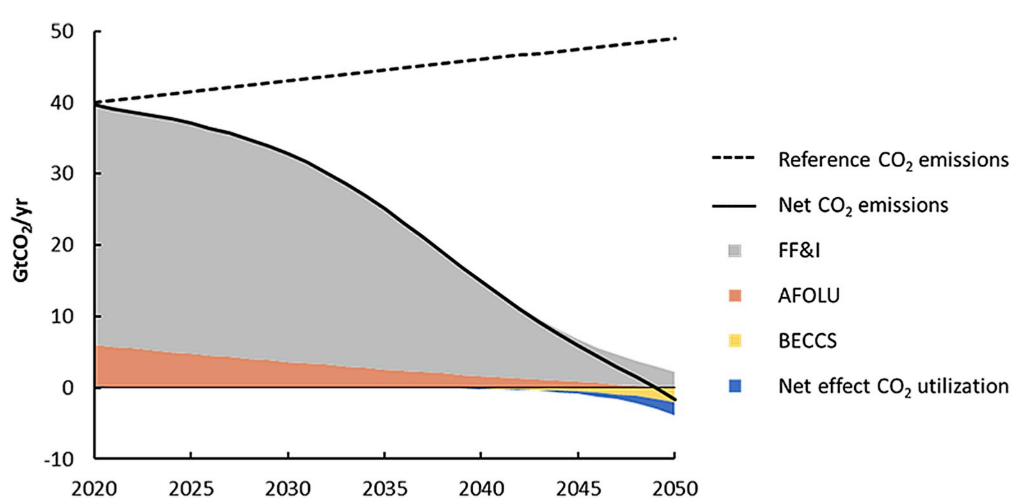

Fig. 4. Transitioning to global net negative CO_2 emissions with a contribution from CO_2 use.

reaching negative CO_2 emissions is available than currently assumed in IAMs if one accounts for all possible CO_2 use processes.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.enpol.2019.110938.

References

Abanades, J.C., Rubin, E.S., Mazzotti, M., Herzog, H.J., 2017. On the climate change mitigation potential of CO_2 conversion to fuels. Energy Environ. Sci. 10, 2491–2499.
Alvarado, M., 2016. The Changing Face of the Global Methanol Market. IHS Chem. Week 10–11. Available from. http://www.methanol.org/wp-content/uploads/2016/07/IHS-ChemicalBulletin-Issue3-Alvarado-Jun16.pdf.
Ampelli, C., Perathoner, S., Centi, G., 2015. CO_2 utilization: an enabling element to move to a resource- and energy-efficient chemical and fuel production. Phil. Trans. R. Soc. A 373, 1–35.
Andersen, K., Peters, G., 2016. The trouble with negative emissions. Science 354 (6309), 182–183 14 Oct 2016.
Aresta, M., Dibenedetto, A., Angelini, A., 2013. The changing paradigm in CO_2 utilization. J. CO_2 Util. 3–4, 65–73.
Armstrong, K., Styring, P., 2015. Assessing the potential of utilization and storage strategies for post-combustion CO_2 emissions reduction. Front. Energy Res. 3, 1–9.
Artz, J., Müller, T.E., Thenert, K., Kleinekorte, J., Meys, R., Sternberg, A., Bardow, A., Leitner, W., 2018. Sustainable conversion of carbon dioxide: an integrated review of catalysis and life cycle assessment. Chem. Rev. 118, 434–504.
Bazzanella, A.M., Ausfelder, F., 2017. Technology study: low carbon energy and feedstock for the European chemical industry. Dechema Gesellschaft für Chem. Tech. und Biotechnol 45–56. Available from. https://dechema.de/dechema_media/Downloads/Positionspapiere/Technology_study_Low_carbon_energy_and_feedstock_for_the_European_chemical_industry-p-20002750.pdf.
Detz, R., Reek, J.N.H., van der Zwaan, B., 2018. The Future of Solar Fuels: when could they become competitive? Energy Environ. Sci. 11, 1653–1669.
Gasser, T., Guivarch, C., Tachiiri, K., Jones, C.D., Ciais, P., 2015. Negative emissions physically needed to keep global warming below 2°C. Nat. Commun. 6, 7958. https://doi.org/10.1038/ncomms8958, 3 Aug 2015.
Geyer, R., Jambeck, J.R., Law, K.L., 2017. Production, use, and fate of all plastics ever made. Sci. Adv. 3, e1700782.
GCCSI, 2011. Global CCS institute. Accelerating the uptake of CCS: industrial use of captured carbon dioxide. Available from. www.globalccsinstitute.com.
IFA, 2017. International fertilizer association, fertilizer outlook 2017-2021, 85th IFA annual conference Marrakech (Morocco). Available from. https://www.fertilizer.org.
IPCC, 2018. Intergovernmental Panel on Climate Change. Special Report, Global Warming of 1.5°C, Summary for Policymakers. Available from. www.ipcc.ch.
IRENA, 2018. Global Energy Transformation - A Roadmap to 2050. Available from. www.irena.org.
Kätelhön, A., Meys, R., Deutz, S., Suh, S., Bardow, A., 2019. Climate change mitigation potential of carbon capture and utilization in the chemical industry. Proc. Natl. Acad. Sci. 116 (23), 11187–11194 4 June 2019.
Keith, D.W., 2009. Why capture CO_2 from the atmosphere? Science 325, 1654–1655.
Lackner, K.S., Brennan, S.A., Matter, J., Park, A.-H.A., Wright, A., van der Zwaan, B.C.C., 2012. The urgency of the development of CO_2 capture from ambient air. Proc. Natl. Acad. Sci. 109 (33), 13156–13162 14 August 2012.
Lindemann, L., 2018. Future Challenges of the Lubricants Industry, FUCHS. Available from. https://www.fuchs.com/fileadmin/Home/Praesentation/2018/180618_FCMD_CTO.pdf.
MacDowell, N., Fennell, P.S., Shah, N., Maitland, G.C., 2017. The role of CO_2 capture and utilization in mitigating climate change. Nat. Clim. Chang. 7, 243–249.
Mikkelsen, M., Jørgensen, M., Krebs, F.C., 2010. The teraton challenge: a review of fixation and transformation of carbon dioxide. Energy Environ. Sci. 3, 43–81.
NAPA/EAPA, 2011. The Asphalt Paving Industry. A Global Perspective. Available from. https://eapa.org/wp-content/uploads/2018/07/GL101-2nd-Edition.pdf.
OCI, 2016. Annual Report 2015. . www.oci.nl.
Sandalow, D., Aines, R., Friedmann, J., Mccoy, S., 2017. Carbon Dioxide Utilization Draft October 2017. Available from. https://e-reports-ext.llnl.gov/pdf/892916.pdf.
Scrivener, K.L., John, V.M., Gartner, E.M., 2016. Eco-efficient cements: potential, economically viable solutions for a low-CO2, cement- based materials industry. Available from. http://wedocs.unep.org/bitstream/handle/20.500.11822/25281/eco_efficient_cements.pdf.
Shell, 2018. Sky Scenario, Meeting the Goals of the Paris Agreement. Available from. www.shell.com.
Stahel, W.R., 2016. The circular economy. Nature 531, 435–438.
van der Giesen, C., Kramer, G.J., 2014. Energy and climate impacts of producing synthetic hydrocarbon fuels from CO_2. Environ. Sci. Technol. 48, 7111–7121.
Zevenhoven, R., Eloneva, S., Teir, S., 2006. Chemical fixation of CO2 in carbonates: routes to valuable products and long-term storage. Catal. Today 115, 73–79.